# Observation and modelling of dusty, low gravity L, and M dwarfs

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**Abstract.** Observational facilities allow now the detection of optical and IR spectra of young M- and L-dwarfs. This enables empirical comparisons with old M- and L- dwarfs, and detailed studies in comparison with synthetic spectra. While classical stellar atmosphere physics seems perfectly appropriate for old M-dwarfs, more physical and chemical processes, cloud formation in particular, needs to be modelled in the substellar regime to allow a detailed spectral interpretation.

Not much is known so far about the details of the inset of cloud formation at the spectral transition region between M and L dwarfs. Furthermore there is observational evidence for diversity in the dust properties of objects having the same spectral type. Do we understand these differences? The question is also how young M- and L-dwarfs need to be classified, which stellar parameter do they have and whether degenerations in the stellar parameter space due to the changing atmosphere physics are present, like in the L-T transition region.

The Splinter was driven by these questions which we will use to encourage interactions between observation and theory. Given the recent advances, both in observations and spectral modelling, an intensive discussion between observers and theoreticians will create new synergies in our field.

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## 1. INTRODUCTION

The late-type M and L dwarfs span a critical regime over which both the internal and atmospheric properties of low mass stellar objects make important transitions. Internally, this regime encompasses the hydrogen burning mass limit ($\sim 0.072\ M_{sun}$ for solar metallicity) for ages typical of the Galactic disk. Young M and L dwarfs in star forming regions ($\tau \sim$ 1-10 Myr) or young associations ($\tau \sim$ 10-100 Myr) are likely to be among the lowest-mass brown dwarfs currently known, while their counterparts in the field may be among the longest-lived low-mass stars in the Galaxy. The age and mass of a brown dwarf is directly related to its surface gravity, which can be discerned in that source's spectral properties. The atmospheres of M and L dwarfs are also host to condensable species of refractory elements, which have a prominent effect on atmospheric opacity and overall spectral energy distributions. These condensable constituents of the atmospheric gas are likely to form grain particles whose chemical and structural composition and spatial distribution are only beginning to be explored in detail [1, 2].

Observationally, the near- and mid-infrared spectra and colours of “normal” late-type M and L dwarfs are seen to exhibit a wide range of variations within a given spectral subclass. $J - K_s$ colours for L dwarfs with similar optical spectra can vary by over one magnitude, and near-infrared spectral slopes for these sources exhibit a comparable range of variation (e.g., [3, 4, 5]). Such variations have been attributed to changing cloud characteristics like cloud thickness, inhomogeneous cloud distributions, and/or changing opacity properties of the clouds and have stymied efforts to derive a complete classification scheme for L dwarfs in the near-infrared (e.g., [6, 7]). Specific peculiar features, such as the presence of enhanced VO and $H_2O$ absorption, unusually weak alkali lines, and peculiar spectral peaks in the near-infrared are discerned in the spectra of very low-mass M and L dwarfs in young associations (e.g., [8, 9]) and in some seemingly “isolated” sources (e.g., [10, 11]); these have been attributed to surface gravity effects. Even metallicity can play a significant role in shaping the observed spectra of M and L dwarfs (see contributions in the “Ultracool Subdwarfs” splinter session). More often than not, M and L dwarf spectra and colours are a function of several parameters– i.e., effective temperature, surface gravity, cloud properties, metallicity and possibly unresolved multiplicity. Disentangling these parameters is essential if we are to both accurately characterise individual sources of interest and provide better observational constraints on rapidly advancing theoretical models. The contributions below provide a snapshot of the current state-of-the-art in the characterisation of dusty and low surface gravity M and L dwarfs from both observational and theoretical perspectives.

## 2. USING NEAR-IR SPECTROSCOPY TO DETERMINE THE AGES OF YOUNG BROWN DWARFS (ALLERS ET AL.)

The near-infrared (near-IR) is the ideal wavelength range for detailed studies of M and L type brown dwarfs, whose spectral energy distributions (SEDs) peak in the near-IR, and may be affected by attenuation from interstellar dust. Additionally, laser guide star adaptive optics (AO) has recently made several remarkable discoveries, many of which can only be followed up in the near-IR, which further motivates detailed study of brown dwarfs in the near-IR.

Ages (and masses) for young brown dwarfs are typically determined by placing them on an H-R diagram using luminosities measured photometrically and effective temperatures determined from spectral types and overlaying evolutionary models (e.g. [12, 13, 14]). H-R diagram inferred ages rely heavily on the accuracy of evolutionary models (which are very uncertain at low masses and young ages), and can be affected by binarity, distance uncertainties, dust extinction, occultation from a circumstellar disk, and accretion history (see poster by Gallardo et al.). We can avoid these problems by using features in the near-IR to determine the ages of our sources.

We have assembled a sample of over 80 moderate resolution (R=750-2000) near-IR spectra of brown dwarfs. Our sample includes objects in the 1–3 Myr old star forming regions of Ophiuchus, Lupus, Taurus, ChamI, ChamII, and IC348, the 5 Myr old Upper Scorpius OB Association (includes objects from [15]), the 10 Myr old TW Hydra moving group, and the ∼Gyr old field population (from [16]). Our objects have spectral types from M5 to L2. We place our young cluster objects (association ages of 1–3 Myr) on the H-R diagram using luminosities and effective temperatures from the literature, and find our objects have a spread in H-R diagram ages of <1 to over 100 Myr! Is the age spread real? Are clusters coeval? Do brown dwarfs have a disparate formation history from stars?

To find the ages of our the objects in our sample, we look at the depths of the alkali (NaI and KI) lines, which are known to increase with age (e.g. [17, 11]). We find that the line equivalent widths of our young (1–3 Myr) cluster objects are significantly lower than seen for objects of the same spectral type in 5 Myr old Upper Sco or 10 Myr old TW Hydra, this argues that the H-R diagram inferred age spread is not real. Using near-IR NaI and KI lines, differences in age of ∼3 Myr can be determined for young brown dwarfs.

## 3. THE DRIFT-PHOENIX MODEL GRID (WITTE ET AL.)

Condensation becomes a major issue in late type dwarfs. In order to approximate this influence, the general-purpose stellar atmosphere code PHOENIX [18] incorporated the very basic DUSTY / COND dust model [19]. Although these models have been able to improve the synthetic spectra and are fairly accurate for $T_{\rm eff}$ above 2500 K (DUSTY) and $T_{\rm eff} < 1000$ K (COND), they either over- or underestimate the dust cloud in the model atmospheres. A more detailed dust treatment is required to reproduce observations for effective temperatures between 1000 K and 2500 K. Therefore, the latest PHOENIX version includes the phase non-equilibrium DRIFT model by [20], which takes into account nucleation with a subsequent kinetic growth and evaporation of dust grains, made of a mixture of 7 different solid species, accompanied by gravitational settling and element replenishment by convective overshooting [2, 21, 22]. The opacities of the mixed dust grains are calculated by effective medium and Mie theory [23].

A DRIFT-PHOENIX model grid for $T_{\rm eff}$=1500...3000 K, ranging over $\log g$=3.0...6.0 and [M/H]=$-$6.0...+0.5 is almost complete. We find a dust cloud structure of five characteristic regions in all our models. Starting from the highest altitudes, there is a (1) nucleation dominated region, followed by a first growth region (2), a region dominated by gravitational settling (3), caused by the strong gas phase depletion, a second growth region (4) due to the end of nucleation and an evaporation region (5). For decreasing effective temperature, the dust clouds become more expanded and more dense, resulting in stronger dust features in the atmosphere structure and the corresponding spectra. While clouds exist up to $T_{\rm eff}$=2500K for $\log g$=3.0, they persist to $T_{\rm eff}$=2800 K for $\log g$=6.0, because the clouds are shifted to higher gas densities, resulting in a more efficient dust growth.

## 4. YOUNG, LOW SURFACE-GRAVITY L DWARFS IDENTIFIED IN THE FIELD: A TENTATIVE LOW-GRAVITY SPECTRAL SEQUENCE (CRUZ ET AL.)

We present an analysis of existing optical spectroscopy of 23 L dwarfs that display unusual spectral features, including weak FeH molecular absorption and weak NaI and KI doublets. All of these features are attributable to low-gravity and indicate that these objects are young, low-mass brown dwarfs. Twenty-one of these L dwarfs were uncovered during our search for nearby, late-type objects using the Two Micron All-Sky Survey while two were identified in the literature. These spectra form an optical low-gravity spectral sequence extending from L0 to L5. Many of these low-gravity L dwarfs have southerly declinations and distance estimates within 60 pc. Their implied youth, on-sky distribution, and distances suggest that they are members of nearby, intermediate-age ($\sim$10–100 Myr), loose associations such as the $\beta$ Pictoris moving group, the Tucana/Horologium association, and the AB Doradus moving group. However, before ages and masses can be confidently adopted for any of these low-gravity L dwarfs, additional kinematic observations are needed to confirm cluster membership.

## 5. CROSSTALK OF DUST PROPERTIES AND LOW-GRAVITY FEATURES (LOOPER ET AL.)

The spectroscopic characteristics of young, late M and early L dwarfs have been empirically noted in young clusters and nearby moving groups. These features include weak hydrides and alkali lines, strong $H_2O$ and VO absorption, and a markedly triangular $H$-band in comparison to normal field dwarfs. The identification of these features has allowed brown dwarfs discovered in the field without any known association to be classified as young (on the order of less than 100 Myr). To date, no mid-to-late L dwarfs in young clusters are known, leaving it unclear as to whether all or some of these characteristic features of youth persist at lower temperatures. Several late L dwarfs, such as 2MASS 2148+4003, have been discovered which mimic some signs of youth but not others - a triangular $H$-band and weaker alkali lines but having weaker $H_2O$ and typical hydride absorption compared to field dwarfs. VO absorption no longer persists down to these lower temperatures. However, the interpretation of these features as the result of youth is counteracted by their kinematics, which show high proper motions and slow rotational velocities, suggesting that these objects are actually old. These results show that at late L spectral types these empirical trends should be used with caution to classify objects as young in the field. They also highlight the need for identification of late L fiducials in clusters.

## 6. ATMOSPHERIC PARAMETERS OF FIELD L AND T DWARFS (CUSHING ET AL.)

We have compared the 0.9 to 14.5 micron spectra of 7 L and 2 T dwarfs to the synthetic spectra generated by the model atmospheres of Marley & Saumon [24]. This is the first time L and T dwarf spectra with such broad wavelength coverage have been compared to synthetic spectra. The grid of spectra, computed in chemical equilibrium, cover from 700 to 2400 K in steps of 100 K, have 3 gravities ($\log g$ = 4.5, 5.0, 5.5 [cm s$^{-2}$]), and 5 sedimention efficiencies ($f_{\rm sed}$ = 1, 2, 3, 4, nc).

Overall, the models fit the data well, although there are are discrepancies near 3 microns in the late L and early T dwarfs (see however the contribution by D. Stephens). The derived effective temperatures agree with those derived using evolutionary models and observed bolometric luminosities [25]. Fits to individual photometric bands almost always produce excellent fits to the data, but the derived effective temperatures can show a large scatter compared to those derived by fitting the full spectra; deviations are typically $\sim$200 K, but can be much larger. In some cases, the resulting best fitting models are completely inconsistent with the rest of spectral energy distributions which suggests that atmospheric parameters derived over narrow wavelength ranges should be considered with caution. The best fitting model of the very red ($J-Ks = 2.05$) L4.5 dwarf 2MASS J2224-0158 implies that it has very thick condensate clouds (fsed=1) and a low surface gravity ($\log g = 4.5$). However the model does not match the data well indicating that deriving atmospheric parameters for dusty and/or low $\log g$ L dwarfs using broad wavelength spectra remains difficult.

## 7. COMPARATIVE STUDY OF CLOUD FORMATION IN BROWN DWARF ATMOSPHERE MODELS (HELLING ET AL.)

Model simulations for Brown Dwarfs have been challenged by the need of including clouds which act as opacity source and element sink. Two main streams developed over the recent years: One approach treats the cloud in their final state of condensation, namely in phase-equilibrium (Tsuji, Cooper et al., Allard et al., Ackerman & Marley). The other approach treats the actual formation process, hence treating the dust formation as kinetic process (Helling & Woitke). We ([26]) compare our dust cloud models in *test case 1* for a given $(T, p, v_{\rm conv})$ structure excluding all uncertainties in the radiative transfer treatment, and in *test case 2* for given ($T_{\rm eff}$, logg) combination taking into account the entire atmosphere simulation. *Test case 1* demonstrates that differences are apparent in our results e.g. in the amount of dust produced, or the grain size distributions inside the cloud. We further studied the abundance of certain molecules in the remaining gas phase, and the phase-non-equilibrium approach would always produce the highest abundances concerning those element involved into dust formation in and above the cloud layer. *Test case 2* allows to compare e.g. integrated fluxes where we find that single models might suggest extreme values but the mean values over all models do recover the spectral type of the object for our sample of four models for a given stellar parameter combination. Note that e.g. SETTL-PHOENIX would not reproduce observations for L dwarfs with the code-version used in this comparison study.

## 8. OBSERVATIONS AND ANALYSIS OF LOW-MASS BENCHMARK STARS (HEITER ET AL.)

We report on a project to establish a set of benchmark stars in the M dwarf region. The goals of this project are two-fold: 1) We aim to improve the effective temperature scale for M dwarfs. 2) We seek to establish a reliable calibration of metallicity, in particular at the high-metallicity end. Our means to achieve these goals are based on high-resolution spectroscopic observations in the red and near-infrared (with UVES and CRIRES at ESO's VLT). The data are analysed using synthetic spectra based on MARCS stellar atmosphere models [27] and recent atomic and molecular line lists in order to constrain element abundances and temperatures of the program stars. The targets span spectral classes from M0 to M4 and fall in the metallicity range of $-0.5$ to $+0.5$ dex. A significant fraction of the program stars are in binary systems with companions of earlier type, and both components are being studied in order to better constrain the stellar parameters. The results of this study will be applied in two different areas: 1) The exploration of the metallicity distribution for M dwarf planet hosts in comparison to solar-type hosts will be made possible [28]. 2) For the analysis of data obtained by ESA's Gaia mission, M dwarf benchmark stars are needed to calibrate the astrophysical parameter determination and to provide templates for radial velocity measurements. Although we confine ourselves in the first phase of this project to early M types where dust formation in the atmospheres is negligible, an extension of the program stars towards lower masses is anticipated in later phases.

## 9. CONCLUSIONS & OUTLOOK

The work presented at this splinter demonstrate the remarkable progress on the field of young low mass stars and brown dwarfs in the last years, both from new observations and from sophisticated theory. So far, the determination of the physical properties of young low mass objects relied fully on theoretical predictions of their colours and luminosities. But theory remained largely unverified due to the scarcity of young calibrators. Decent spectra existed only for a handful of these young brown dwarfs and allowed only a first assessment of their spectral features to determine their properties and to identify their age. Now we see that observers provide us with an ever growing number of spectra of young brown dwarfs, allowing for the first time a systematic study of their observational properties.

With plurality comes diversity and we are faced with the challenge of developing a multi-dimensional classification scheme that includes at least three properties, i.e. surface gravity, metallicity, and effective temperature. The fact that all these properties are interlinked and a function of age adds to the level of complexity involved in this task. The number of "peculiar" objects is growing, indicating that we have either not fully understood the possible crosstalk of different properties or that brown dwarfs are showing more signs of individualism than stars. This should not dilute the need for the in-depth characterisation of a few benchmark objects. Especially the determination of accurate metallicities for these objects will be difficult and provides already a challenge for regular (old) M dwarfs.

On the other hand, the theoretical description of the spectral features of young and dusty objects has made tremendous progress. Different modeller groups were present showing their results and demonstrated the diversity in the field. Models with different physical assumptions on dust treatment, namely assuming phase-equilibrium (Marley et al., Freytag et al.) or applying kinetic treatments (Helling et al., Witte et al.), produce very different predictions on the spectral properties of brown dwarfs. Observers should feel encouraged to not only hook with one particular model but compare different "flavours" and also keep in mind the individual "trust range" of the models when assigning physical properties, such as mass and age, based on spectral fits. Note that the comparison study included here concerns atmosphere simulations only, and not the modeling of the Brown Dwarfs evolution.

Although the drive in our field goes into ever cooler objects down to the planetary regime, young brown dwarfs keep providing surprises. Key issues still remain little understood such as the inset of dust formation at the M/L type transition and its effect on the observable properties of these objects. New telescopes and instruments, suitable for studying brown dwarfs, become available in the next decade, such as WISE and NIRCam at the *JWST* or instruments at the next generation of ground based large telescopes, such as the ELT. Multi-wavelength studies in the near- and thermal-Infrared with unprecedented sensitivities and/or extremely high spatial and spectral resolution will provide further and new insides into the atmosphere chemistry of such ultra-cool objects but also into the formation scenario of brown dwarfs.

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